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An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis

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ABSTRACT

Glacial lake outburst floods (GLOFs) are a unique type of natural hazard in the cryosphere that may result in catastrophic fatalities and damages. The Himalayas are known as one of the world's most GLOF-vulnerable zones. Effective hazard assessments and risk management require a thorough inventory of historical GLOF events across the Himalayas, which is hitherto absent. Existing studies imply that numerous historical GLOF events are contentious because of discrepant geographic coordinates, names, or outburst time, requiring further verifications. This study reviews and verifies over 60 historical GLOF events across the Himalayas using a comprehensive method that combines literature documentations, archival remote sensing observations, geomorphological analysis, and field investigations. As a result, three unreported GLOF events were discovered from remote sensing images and geomorphological analysis. Eleven suspicious events were identified and suggested to be excluded. The properties of five outburst lakes, i.e., Degaco, Chongbaxia Tsho, Geiqu, Lemthang Tsho, and a lake on Tshojo Glacier, were corrected or updated. A total of 51 GLOF events were verified to be convincing, and these outburst lakes were classified into three categories according to their statuses in the past decades, namely disappeared (12), stable (30), and expanding (9). Statistics of the verified GLOF events show that GLOF tended to occur between April and October in the Himalayas. We suggest that more attention should be paid to rapidly expanding glacial lakes with high possibility of repetitive outbursts. This study also demonstrates the effectiveness of integrating remote sensing and geomorphic interpretations in identifying and verifying GLOF events in remote alpine environments. This inventory of GLOFs with a range of critical attributes (e.g., locations, time, and mechanisms) will benefit the continuous monitoring and prediction of potentially dangerous glacial lakes and contribute to outburst-induced risk assessments and hazard mitigations.

1. Introduction

A glacial lake outburst flood (GLOF) is a unique natural hazard that occurs in the cryosphere when a moraine dam failed with a subsequent sudden release of water from the glacial lake (Westoby et al., 2014a, 2014b). Historical GLOFs in the Himalayas have caused catastrophic fatalities and destructions in the downstream zones (ICIMOD (The International Centre for Integrated Mountain Development), 2011), for example, the outbursts of Cirenmaco in 1981, located in the Sun Koshi River basin in China (Xu and Feng, 1989; Chen et al., 2007; Wang et al., 2015a), Dig Tsho in 1985 (Richardson and Reynolds, 2000; Bajracharya et al., 2007) and Tam Pokhari in 1998, located in Dudh Koshi in Nepal (Xu and Feng, 1989; Mool et al., 2001; Kattelmann, 2003; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017), and Chorabari Lake in 2013, located in the Alaknanda River basin in India (Durga Rao et al., 2014; Das et al., 2015). The Himalayas (Fig. 1), occupying a total area of ~0.65 million km^2 and containing 22,800 km^2 glaciers (Bolch et al., 2012; Nie et al., 2017), are known as one of the world's major GLOF-vulnerable regions (Quincey et al., 2005; Carrivick and Tweed, 2016; Nie et al., 2017). Glacier recession in response to climate warming has resulted in the formation and expansion of Himalayan glacial lakes (Kang et al., 2010; Nie et al., 2013, 2017; Song et al., 2017) and increased the risk of GLOFs, which deserve increasing attention owing to their potential catastrophic damages.

A database of GLOF events compiled from existing literature is essential to reveal the process and mechanism of GLOFs for hazard assessment, mitigation, and consequently risk management. GLOF events have been reported in the Bhutan Himalayas (Geological Survey of

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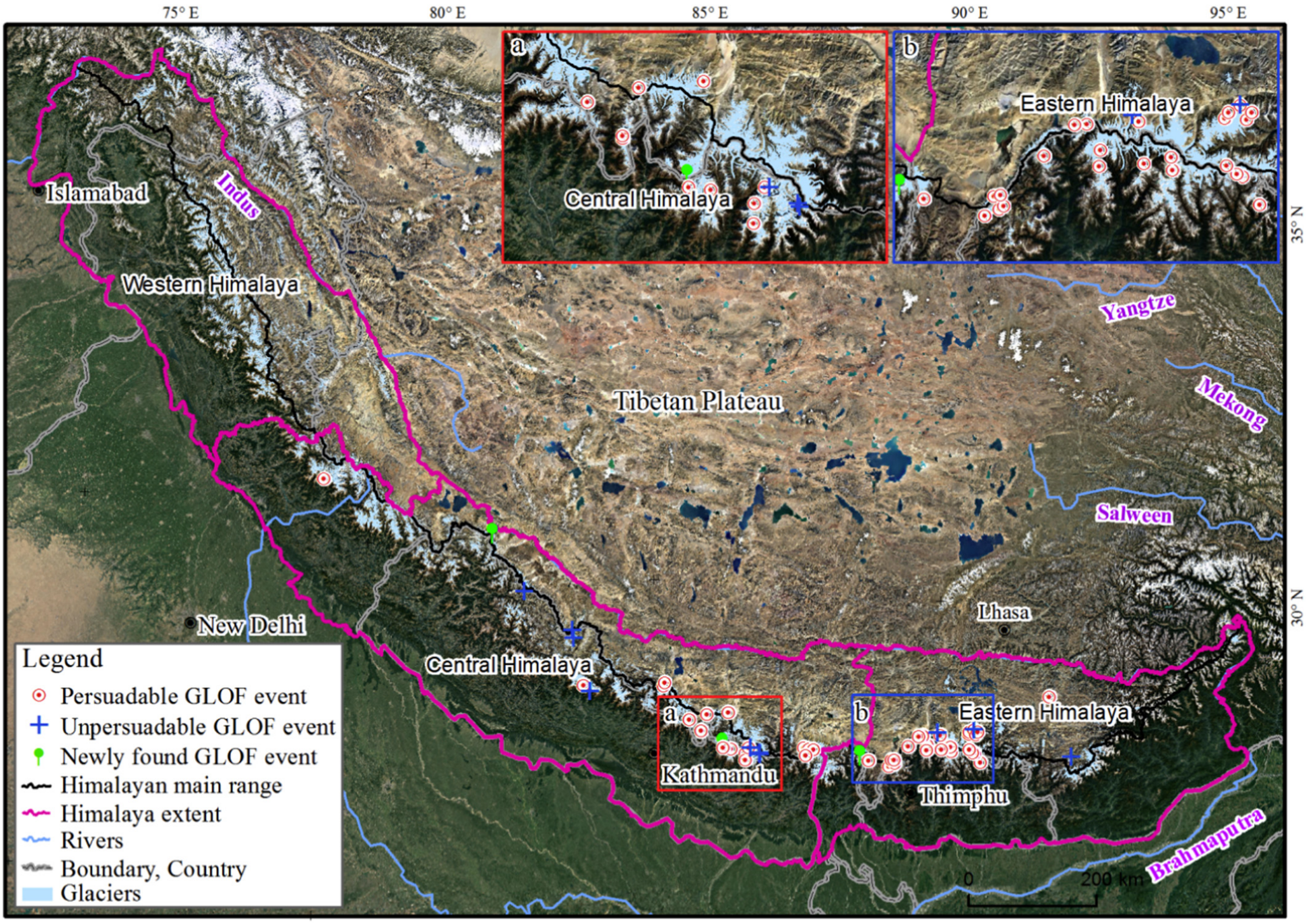

Fig. 1. Distribution of historical GLOFs in the Himalayas; the background image is from ESRI's world basemap.

Bhutan, 1999; Komori et al., 2012), in Tibet, China (Liu et al., 2014; Yao et al., 2014), Nepali (Bajracharya et al., 2008; ICIMOD, 2011), and Indian Himalayas (Durga Rao et al., 2014; Das et al., 2015) from literature, media reports, and remote sensing data. However, as most GLOFs occurred in remote and less inhabited regions, low data availability or quality can cause substantial misunderstandings, especially for the GLOF events that happened prior to the era of satellite remote sensing. The definition of GLOF in the Himalayas is still under debate. For example, some scholars argue that a debris flow that occurred on 10 Aug. 2007 in Cona County is a GLOF event (Yao et al., 2014). However, the original reference focused on the causes and prevention countermeasures of the debris flow hazard (Mo et al., 2008). We support the original authors in that this event was a debris flow hazard induced by heavy rainfall rather than a GLOF. Some studies did not provide detailed spatial locations of those lakes (e.g., longitude and latitude); thus readers do not know where the GLOFs explicitly occurred (Xu and Feng, 1989; ICIMOD, 2011; Falátková, 2016). Other studies even reported wrong locations of certain GLOF events, such as the Jinco event (Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014), which was later corrected by Yao et al. (2014) to Yindapuco. Some same GLOF events have been assigned by different coordinates, such as the Degaco event (Liu et al., 2014; Yao et al., 2014). Another study (Komori et al., 2012) confused the Degaco event in Luozha County with the Poge Tsho event on 23 July 1972 in Suoxian County. An outburst event in 2001 based on multitemporal satellite observations and our field investigation was named to Longjiu Tsho (Yao et al., 2014) or Chongbaxia Tsho (Liu et al., 2016) on 6 Aug. 2000, which was previously referred to as 'unknown' during 2000–2001 (Komori et al., 2012). Such inconsistent naming and occurrence time (Carrivick and Tweed, 2016) need to be verified and preferably unified. All the above issues imply that the reported GLOFs should be further validated. The existing literature however lacks a systematic inventory of GLOFs across the entire Himalayas, such as outburst lakes' past condition, current status, future projection, and their chronological characteristics.

An accessible online database of GLOFs, such as proposed by Vilímek et al. (2014), makes a significant contribution to facilitating hazard assessment and risk management. An effective modern tool to monitor and analyze the historical GLOFs in the less accessible high mountain areas is provided via satellite remote sensing, especially, the use of optical images such as the Landsat images with long archival records since 1972. Geomorphic evidence, e.g., V-shaped trench, huge debris deposits, and devastated river beds in accordance with remote sensing data, has been employed to identify historical outburst events (Komori et al., 2012). These features, however, could also be formed in other cryo-hydrologic events rather than GLOFs. Therefore, caution must be paid when using satellite observations alone to identify a GLOF event. A more rigorous method for GLOF verifications requests the synergy of multisource evidence, such as historical documents, field surveys, long-term satellite observations, and high resolution image archives (e.g., Google Earth) that can better reveal the hydrogeomorphic processes induced by different GLOF incidents across the Himalayas.

To improve our understanding of GLOFs in the Himalayas, this study aims to (i) construct an up-to-date GLOF database across the entire Himalayas; (ii) identify missing GLOF events and distinguish between persuadable and unpersuadable events using a combination of remote sensing and geomorphological analyses; and (iii) reveal the states,

characteristic and recent changes of outburst lakes, including their triggers and damages.

2. Methods

We here compiled a database of historical GLOFs in the Himalayas based on scientific literature, reports, media news, and assessments of glacial lake changes using archival remote sensing observations (see references in Table 1 and Table S1). Collected primary attributes for each event include the outburst lake's name, location (region, country, and coordinates), water level and area before outburst, recent area (in 2015), outburst date, persuadability, triggers, loss/damages, and area trend. Not all properties were available for some events, especially for those earlier ones.

We then determined the exact coordinates of the source glacial lake in each compiled event. Many events missed location information, while others were assigned with erroneous coordinates. Under such circumstances, we located the source glacial lakes by comparing studies for the same event or logical reasoning from geographic description and spatial distribution of glacial lakes and their source glaciers.

Next, we validated each event using geomorphological analysis and remote sensing observations. Geomorphological properties including the characteristics of hydrological basins such as area, drainage networks, slope, appearance of lakes and glaciers were preliminarily analyzed for the possibility of GLOFs, and then followed by visual interpretation of geomorphic features around each glacial lake in remote sensing images, such as V-shaped trench, debris fan, devastation downstream or lacustrine deposition. In addition, area changes for all reported lakes were also monitored by multi-temporal satellite images. High-resolution Google Earth imagery in combination with Glacier Inventory Data (Armstrong et al., 2011; Guo et al., 2015) were employed to identify the geomorphological evidence for each historical GLOF such as V-shaped trench and debris fan. The identified impossible events were classified as unpersuadable.

Owing to limited availability of satellite imagery before 1990, pre-1990 GLOF events were primarily verified by literature review and geomorphological characteristics interpreted from imageries acquired afterward, including V-shaped trench, debris fan, devastation downstream, and lacustrine deposition. Post-1990 GLOF events were verified by archival Landsat 5–8 imageries, Google Earth images, and in situ photographic investigations. The primary evidence includes obvious shrinkage of the lake area and consequent flood sedimentation by comparing imageries before and after reported outbursts. To track the dynamics of glacial lakes after outburst, all source lakes were mapped using available archived Landsat images until present.

Finally, we inspected all rapidly shrinking or disappeared glacial lakes ≥0.05 km^2 to identify a GLOF using the Himalayan glacial lake inventories (Nie et al., 2017) at five episodes (1990, 2000, 2005, 2010, and 2015) with a minimum mapping unit of nine Landsat pixels or 0.0081 km^2. A number of unreported GLOFs were identified and labeled as newly found GLOF events.

3. Historical GLOF events across the Himalayas

3.1. Distribution of GLOF events in the Himalayas

A total of 62 GLOF events initiated from 56 glacial lakes (Figs. 1 and 2, Table 1) in the Himalayas were verified, including three newly identified events in this study. All GLOF events were classified into unpersuadable (11) and persuadable events (51). The persuadable events were primarily located in the eastern (26) and central (25) Himalayas or administratively in China (28), Nepal (8), Bhutan (13), and India (2). Their elevations ranged from 3669 to 5527 m with a mean of 4831 m (Fig. 3).

3.2. GLOF events before 1990

A total of 32 GLOF events occurred before 1990 and were believed to be persuadable according to our verification methods. Most GLOFs occurred at elevations above 4200 m. Fourteen out of 32 events have explicit flooding dates while others do not (Table 1).

Meanwhile, seven GLOF events were validated to be unpersuaded and thus recommended to be excluded from the historical GLOF list. These GLOF events, i.e., Barun Khola West, Barun Khola East, Chokarma Cho, Unnamed 1st, Unnamed 2nd, Unnamed 3rd (Bajracharya et al., 2008) and Huang Tsho (Komori et al., 2012), were previously misidentified as GLOFs primarily using satellite images or aerial photographs (ICIMOD, 2011; Komori et al., 2012). In addition to the unknown outburst dates and damage, the terminal moraine collapses were likely caused by drainage; and direct evidence for these GLOF events is largely unpersuadable.

3.2.1. Barun Khola West and East

For Barun Khola West (Fig. 4A), briefly described only by ICIMOD, lacustrine deposition caused by lake level fluctuations, clean V-shaped breach, and debris fan were not observed in high resolution satellite images. If a GLOF had occurred, the flood would have devastated the downstream river beds from the collapsed dam. However, tiny and crooked rivers seemed to be naturally formed without any drastic damages. For Barun Khola East (Fig. 4B), no trail of terminal moraine collapse from this lake was observed. A debris fan and its upper provenance are clear; however, this geomorphic feature is more like a rainfall-induced landslide. From Barun Khola East (snow-covered in Fig. 4B) to the breach (~1.4 km), no devastation evidence was observed. If this GLOF had occurred, a vanished lake basin would have been visible in the proglacial area. Nevertheless, no geomorphological trace indicated the existence of an outburst lake.

3.2.2. Chokarma Cho

Chokarma Cho (Fig. 4C), located between Lhotse Glacier and Lhotse Shar Glacier, was a lateral moraine-dammed lake (close to Imja Lake) and desiccated before 1975 (the earliest available Landsat observation). An unpaved footpath passing this lake was obviously seen from the Google Earth imagery acquired on 3 Dec. 2016, but devastation downstream and V-shaped breaches that indicate dam failure were not visible.

3.2.3. Unnamed 1st, Unnamed 2nd, and Unnamed 3rd events

The knowledge available on the three anonymous events, i.e., Unnamed 1st, Unnamed 2nd, and Unnamed 3rd, is very limited. The Unnamed 1st event was labeled as 12N in a distribution map of Nepalese recorded GLOFs (ICIMOD, 2011), which was supposed to originate from a moraine-dammed lake (Fig. 4D). The indicated lake was dammed by the downstream moraine of another glacier, which was stable between 29 Oct. 1976 and 28 Sep. 2015. Geomorphological analysis from high resolution images clearly indicated that the deposition fan was originated from a glacier on the upper left side of the watershed rather than the lake 12N. The above geomorphological characteristics do not suggest that the 12N has likely experienced a GLOF thus far.

The Unnamed 2nd event (marked 13N in the ICIMOD, 2011 report) is also impossible because of lack of any GLOF geomorphic features (Fig. 4E). The location of the Unnamed 2nd lake was fully covered by glacier ice in the Landsat image acquired on 29 Oct. 1976. A glacial lake was observed on 19 Oct. 1988 with an area of 0.05 km^2 and gradually increased until 2013. Then, a sudden expansion occurred in 2014, and the lake area reached 0.23 km^2 on 28 Sep. 2015. The evolution of this lake and its unhindered drainage system strongly imply a low possibility of a historical GLOF event. The recently rapid expansion of this glacial lake is storing massive water volume that could possibly cause considerable damage in case of outburst. This lake deserves close monitoring in the future.

Table 1
Historical GLOF events in the Himalayas (please see Table S1 for complete attributes).

Order	Name	Persuadability	Date of outburst	Location	Reference
1	Taraco	Yes	1935-8-28	CHN	Xu and Feng, 1989; Chen et al., 2007; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
2	Qiongbihema Tsho	Yes	1940-7-10	EHS	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017
3	Lureco	Yes	1950s	EHN	Tong et al., 2013; Yao et al., 2014
4	Sangwang Tsho	Yes	1954-7-16	EHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
5	A lake on Cuoalong Glacier	Yes	1955–1966	EHN	Komori et al., 2012
6	Tarina Tsho	Yes	1957	EHS	Geological Survey of Bhutan, 1999; Bajracharya et al., 2008; ICIMOD, 2011; Komori et al., 2012
7	A lake on Lunana Glacier	Yes	1960s	EHS	Geological Survey of Bhutan, 1999; Komori et al., 2012
8	Cirenmaco 1st	Yes	1964	CHS	Xu and Feng, 1989; Chen et al., 2007; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017
9	Longda Tsho	Yes	1964-8-25	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017
10	Gelhaipuco	Yes	1964-9-21	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017
11	Unnamed 4th	Yes	1966–1974	EHS	Ageta and Iwata, 1999; Komori et al., 2012
12	Ayaco	Yes	1968-8-15	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
13	Ayaco	Yes	1969-8-17	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
14	Ayaco	Yes	1970-7-12	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
15	Nare Lake	Yes	1977-9-3	CHS	Mool et al., 2001; Kattelmann, 2003; Bajracharya et al., 2008; ICIMOD, 2011; Gurung et al., 2017
16	Nagma Pokhari	Yes	1980-6-23	CHS	Mool et al., 2001; Bajracharya et al., 2008; ICIMOD, 2011
17	Zharico	Yes	1981-6-24	EHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Yao et al., 2014
18	Cirenmaco 2nd	Yes	1981-7-11	CHS	Xu and Feng, 1989; Chen et al., 2007; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014; Gurung et al., 2017
19	Yindapuco	Yes	1982-8-27	CHN	Xu and Feng, 1989; Bajracharya et al., 2008; ICIMOD, 2011; Liu et al., 2014
20	Dig Tsho	Yes	1985-4-4	CHS	Mool et al., 2001; Bajracharya et al., 2007, 2008; ICIMOD, 2011; Gurung et al., 2017
21	Chhubung	Yes	1991-7-12	CHS	Mool et al., 2001; Bajracharya et al., 2008; ICIMOD, 2011; Wang et al., 2012; Westoby et al., 2014b
22	Upper Langbu Tsho	Yes	1992	CHS	This study
23	Zangla Tsho	Yes	1994	CHN	This study
24	Luggye Tsho	Yes	1994-10-7	EHS	Fujita et al., 2008; Bajracharya et al., 2008; ICIMOD, 2011; Gurung et al., 2017
25	Xiaga	Yes	1995-5-26	EHN	Li et al., 1995; Yao et al., 2014
26	Zanaco	Yes	1995-6-7	CHN	Bajracharya et al., 2008; ICIMOD, 2011; Yao et al., 2014
27	Kongyangmi La Tsho	Yes	1997	EHS	This study
28	Gangri Tsho III	Yes	1998	EHS	Komori et al., 2012
29	Tam Pokhari	Yes	1998-9-3	CHS	Mool et al., 2001; Kattelmann, 2003; Bajracharya et al., 2008; ICIMOD, 2011; Gurung et al., 2017
30	Chongbaxia Tsho	Yes	2001	EHN	Komori et al., 2012; Yao et al., 2014; Liu et al., 2016; This study
31	Jialongco 1st	Yes	2002-5-23	CHS	Chen et al., 2007; Liu et al., 2014
32	Jialongco 2nd	Yes	2002-6-29	CHS	Chen et al., 2007; Liu et al., 2014
33	A supraglacial lake of Tshojo Glacier	Yes	2009-4-29	EHS	Komori et al., 2012
34	Geiqu	Yes	2010	CHN	Yao et al., 2014
35	Choradari Lake	Yes	2013-6-17	CHS	Das et al., 2015; Durga Rao et al., 2014
36	A supraglacial lake of Lotse Glacier	Yes	2015-5-25	CHS	Rounce et al., 2017
37	Lemthang Tsho	Yes	2015-6-28	EHS	Gurung et al., 2017
38	A supraglacial lake of Lotse Glacier	Yes	2016-6-12	CHS	Rounce et al., 2017
39	Gongbatongsha Tsho	Yes	2016-7-5	CHS	Bhote Koshi Power Company Private Limited (BKPC) www.bhotekoshi.com.np; This study
40	Machhapuchhre	Yes	450 years ago	CHS	Mool et al., 2001; Bajracharya et al., 2008; ICIMOD, 2011
41	Chubda Tsho	Yes	Before 1956	EHS	Komori et al., 2012
42	Tarikha Lake	Yes	Before 1956	EHS	Komori et al., 2012
43	Degaco	Yes	Before 1966	EHN	Komori et al., 2012; This study
44	Jhomohari South	Yes	Before 1966	EHS	Komori et al., 2012
45	Jichudrake North 1st	Yes	Before 1966	EHN	Komori et al., 2012
46	Jichudrake North 2nd	Yes	Before 1966	EHN	Komori et al., 2012
47	Simdong Goi Tsho	Yes	Before 1966	EHS	Komori et al., 2012
48	Unnamed 5th	Yes	Before 1966	EHS	Komori et al., 2012
49	Upper Chokham Tsho	Yes	Before 1966	EHS	Ageta and Iwata, 1999; Komori et al., 2012
50	Upper Jiejiu Tsho	Yes	Before 1966	EHN	Komori et al., 2012
51	Upper Shegong Tsho	Yes	Before 1966	EHN	Komori et al., 2012
52	Barun Khola East	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
53	Barun Khola West	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
54	Chokarma Cho	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
55	Huang Tsho	No	–	EHN	Komori et al., 2012
56	Unnamed 1st	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
57	Unnamed 2nd	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
58	Unnamed 3rd	No	–	CHS	Bajracharya et al., 2008; ICIMOD, 2011
59	Degaco	No	2002-9-18	EHN	Liu et al., 2014; Yao et al., 2014
60	Kabache Lake	No	2003-8-15	CHS	Bajracharya et al., 2008; ICIMOD, 2011
61	Kabache Lake	No	2004-8-8	CHS	Bajracharya et al., 2008; ICIMOD, 2011
62	Zhemaico	No	2009-7-3	EHN	Liu et al., 2014; Yao et al., 2014

Notes: Central Himalaya North (CHN), Central Himalaya South (CHS), Eastern Himalaya North (EHN), and Eastern Himalaya South (EHS).

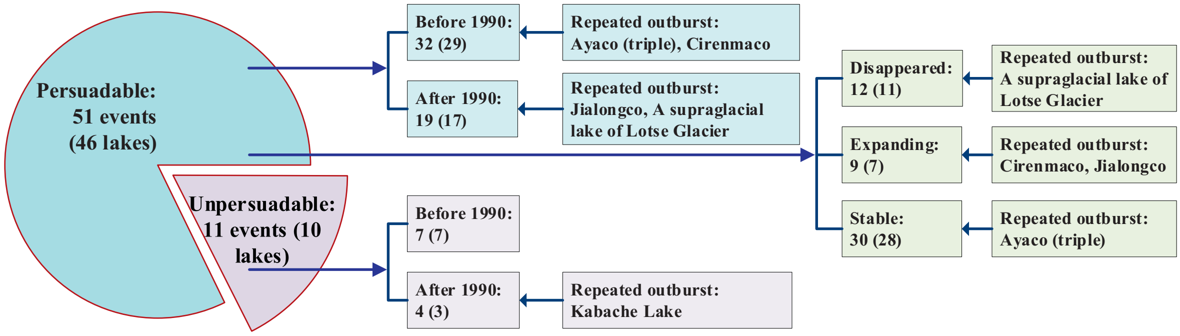

Fig. 2. Outburst numbers of events and lakes for each scenario.

A sharp outlet and debris fan associated with the Unnamed 3rd event (marked as 14N in the ICIMOD, 2011 report) might appear the result of a GLOF. The area of this river basin is ~2.0 km^2, which was usually covered by snow based on satellite observations (Fig. 4F). The lack of high quality images limits our capability to confirm whether a lake formed and outburst occurred in the past. However, the GLIMS glacier inventory based on a 1966 reference map did not show a glacier in this basin (Fig. 4G). Steep basin topography was also not favorable to form a lake. We believe that this Unnamed 3rd event is not persuadable based on the above evidence.

3.2.4. Huang Tsho

An outburst flood from Huang Tsho was first reported by Komori et al. (2012) based on a 1966 Corona photo. They described that the outburst flood occurred before 1966 by overflowing from a 400-m-wide moraine dam on the right side. The lake water currently outflows through the left side of the moraine without a clear V-shaped valley (Komori et al., 2012). However, this GLOF event has never been reported or recorded. We carried out a field investigation on the Huang Tsho in October 2016 to verify the GLOF event (Fig. 4H). Our observations show that the so-called breach of the GLOF at the right lateral moraine is probably a physical result of gravitated erosion (Fig. 4I). Several gullies are clear over the unstable lateral moraine in the photographs, which were possibly caused by precipitation, melted snow, and/or buried ice. The head part of the largest gully is just about 40 m wide, and this gully is ~350 m long, which seems to be a trench from Huang Tsho (Fig. 4J and K). But actually, the highest lake level never reached the head of this gully in accordance with the photographic and geomorphological analysis. Neither does a debris fan related to a GLOF event exist given our meticulous inspection from field investigations and satellite images. Although we have confirmed no previous outburst of Huang Tsho, this lake should be closely monitored in the future owing to its high risk (Wang et al., 2012). It expanded rapidly from 1991 (1.04 km^2) to 2015 (1.78 km^2). Currently, a V-shaped trench formed at the outlet, and the elevation difference from the lake level to the downstream river bed was > 100 m. In case of failure, outburst flooding from Huang Tsho may cause catastrophic damages to the downstream regions because of its high potential flood volume (Fujita et al., 2013).

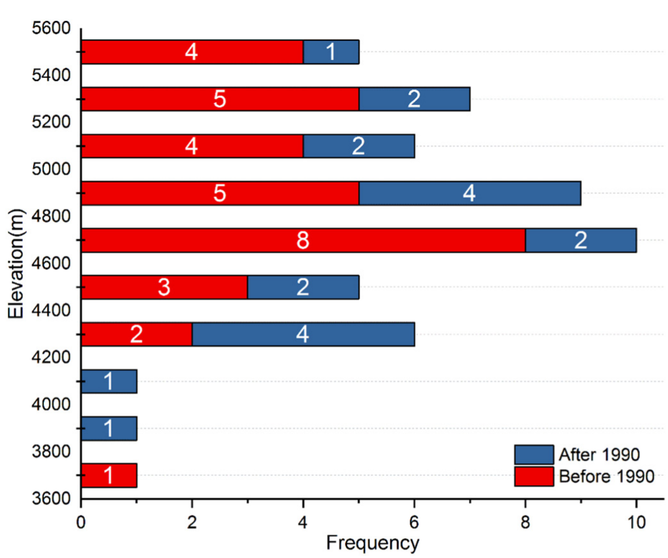

Fig. 3. Altitudinal distributions of Himalayan historical GLOF events.

3.3. GLOF events after 1990

3.3.1. Newly found historical GLOF events

We identified three previously undocumented GLOF events (Fig. 5). The first GLOF event (86.447217°E, 27.929294°N) is located within the Sun Kosi watershed and at the town of Rongxia, Tibet, China. The associated lake, Upper Langbu Tsho, is named after the closest Langbu Tsho with the same mother glacier (GLIMS glac_id of G086454E27926N). Based on a continuous satellite tracking of this glacial lake (Fig. 4A), the outburst date was between 22 Sep. 1992 and 17 Nov. 1992. The lake area increased rapidly from 0.06 km^2 in 1989 to 0.24 km^2 on 22 Sep. 1992, followed by a sharp shrinkage after two months on 17 Nov. 1992 (0.06 km^2), and then remained relatively stable until 2015. The lake was connected to the glacier terminus before its outburst in 1992 and detached after 2009 (Fig. 5A and D). Ice avalanche possibly triggered this GLOF given a steep ice cliff and a rapid retreat of the glacier.

The second GLOF event (82.118101°E, 30.355574°N) is located within the Maquan River basin, Tibet, China. This lake is entitled Zangla Tsho in accordance with the downriver Zanglaqu. Satellite observations suggest that Zangla Tsho GLOF occurred between April and October in 1994 (Fig. 5B and E). Zangla Tsho kept stable between 10 Oct. 1988 and 27 Dec. 1993 with an area of 0.21 km^2 and rapidly shrunk to a very small lake (0.01 km^2 on 27 Oct. 1994) after the outburst. Lacustrine deposition is clearly observed in a high resolution image on 2 Dec. 2005. The lake was already disconnected from its upstream glacier (GLIMS glac_id of G082129E30336N) in 1988 by at least ~400 m. The clean glacier upstream retreated fast from 1988 to 2015. The trail of landslide or rock fall is not observed around the glacial lake. A glacial lake was located at the upstream tributary and shrunk by 17.6% from 27 Dec. 1993 to 27 Oct. 1994. Drainage from this lake to the flooded downstream lake appears evident in the high resolution image (Fig. 4E). The water inflow from the upstream lake likely caused the dam failure of the downstream lake and triggered its outburst flood.

The third event (Kongyangmi La Tsho, 88.782077°E, 27.901247°N) is located in Tista basin and occurred between April and October in 1997 (Fig. 5C and F). This lake was 0.24 km^2 on 14 June 1990, expanded dramatically to 0.55 km^2 on 8 Nov. 1991, and generally stabilized between 1991 and 1996. After the outburst in 1997, the glacial lake remained stable until 2015 (~0.28 km^2). The frontal edge of this glacial lake retreated

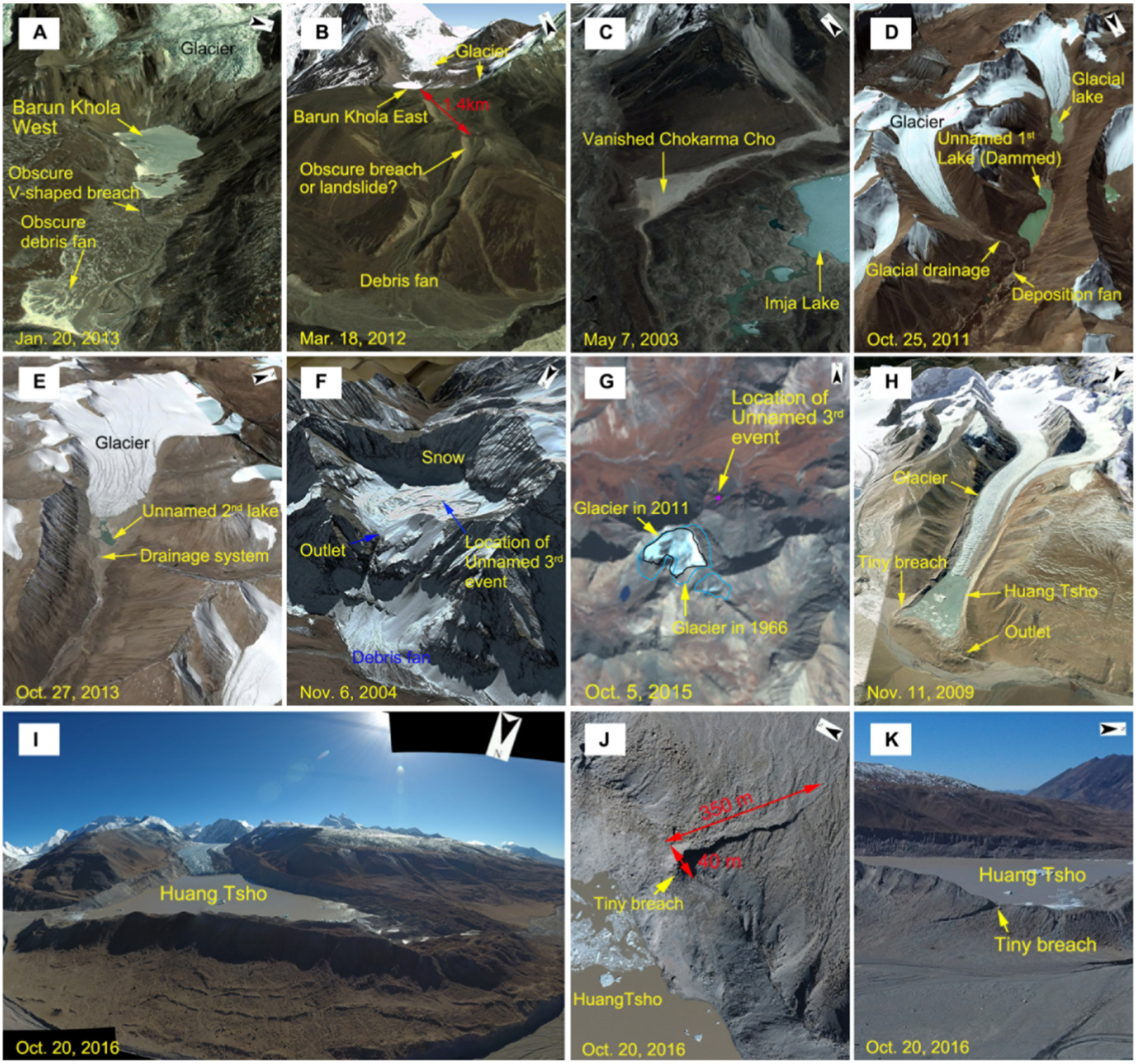

Fig. 4. Geomorphic characteristics near the unpersuadable GLOF events based on Google Earth images (A–H) and in situ photos (I–K).

by > 200 m after the outburst caused by the lake level drop. The left trailing edge of this glacial lake retreated by > 120 m and advanced deposition as a result of upstream ice avalanche. It is most likely that an ice avalanche occurred on the left side of the main glacier (GLIMS glac_id of G088819E27930N) and that the mass movement of the ice avalanche plunged into the glacial lake (Fig. 2F), which triggered this GLOF event.

3.3.2. Corrected/updated GLOF events

Erroneous geographic coordinates or occurrence times are misleading and prevent researchers from unfolding the process or mechanism of a GLOF event. This study corrects or updates the previously reported characteristics of the following historical GLOF events.

3.3.2.1. Degaco. Degaco (Fig. 6) was first reported to be located in Luoza County (28°07′25″N, 90°34′01″E) (Liu et al., 2014) where a pro-glacial lake was connected to the Wenjia Glacier (Fig. 6C). No geomorphological evidence could be found from remote sensing imagery to verify a GLOF near this lake. We therefore conclude that the report about this GLOF event in Liu et al. (2014) is questionable.

In another study, researchers thought that Degaco was located at 28.33°N, 90.67°E according to literature descriptions and Google Earth images, which burst on 18 Sep. 2002 (Yao et al., 2014). This location of Degaco was the same as another GLOF event called Poge Tsho that was believed to occur before 1966 in accordance with a Corona satellite photo (Komori et al., 2012). We agree with Komori et al. (2012) that this lake burst before 1966 (as shown in Fig. 5D). However, Komori et al. named this lake Poge Tsho because of the GLOF event in 1972 reported by Xu and Feng (1994). Other studies (Xu and Feng, 1989, 1994; Liu et al., 2014; Yao et al., 2014) have demonstrated that Poge Tsho was located in Suoxian County (not in Luoza County), which caused a flood on 23 July 1972. We here verify that the correct name of this lake to be

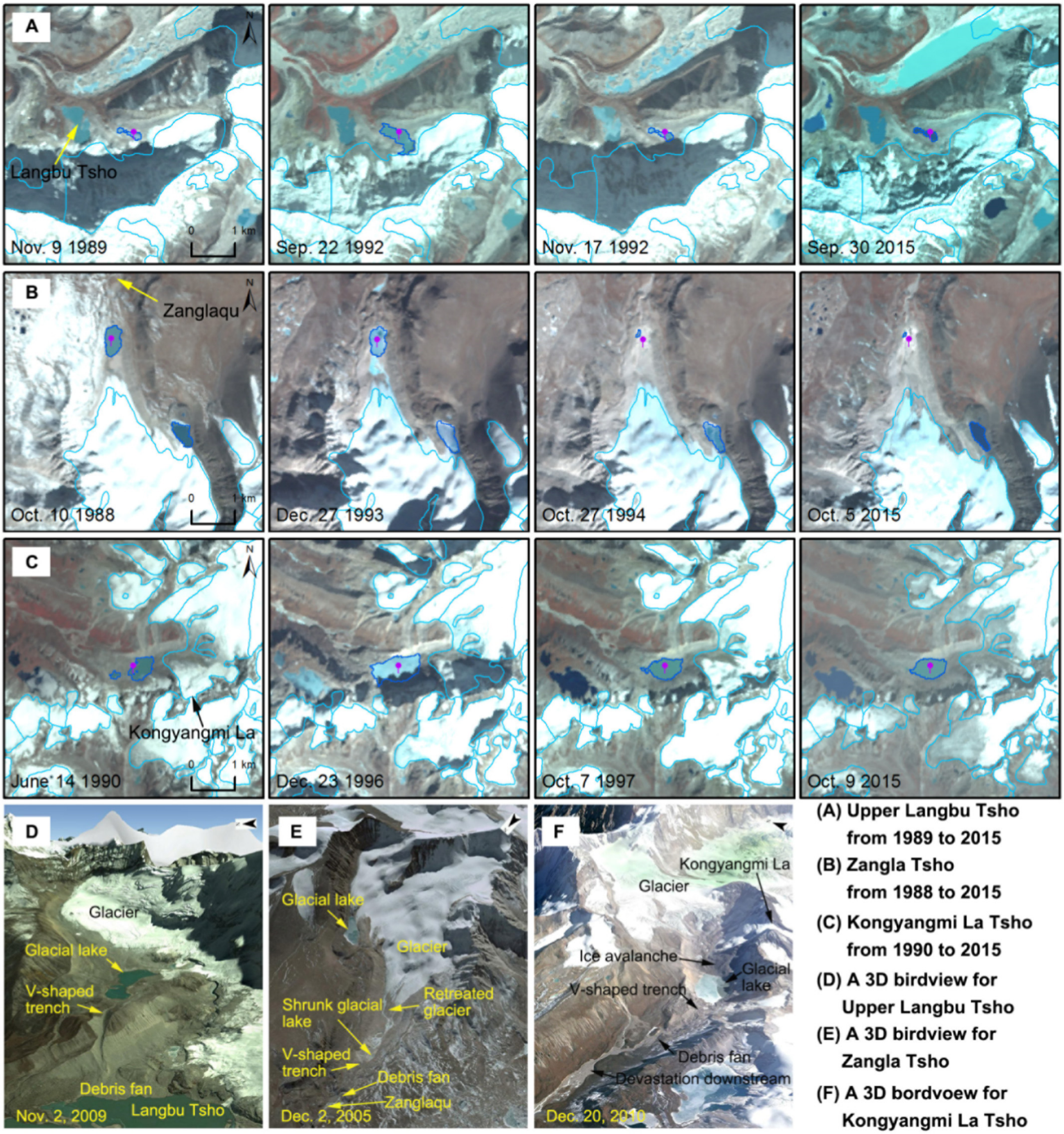

Fig. 5. Landsat observations of lake dynamics (A–C) and geomorphic characters from Google Earth images (D–F) for the three newly found GLOF events.

Degaco as labeled in Google Earth and Tianditu provided by the National Administration of Surveying, Mapping and Geoinformation, China. Did this lake burst twice (i.e., before 1996 and in 2002)? The answer is no given our interpretation of archival imagery and field survey. Evident downstream surface damage was not observed in images acquired between 2000 and 2002 (Fig. 6A). Areas of this lake (~1.12 km^2) remained stable from 2000 to 2015. The fresh gravels and sands on the old debris fan stay similar in the photos taken in 1966 and in 2016 (Fig. 6D and E). At this point, the original glacial lake that caused a flood on 18 Sep. 2002 cannot be confirmed. Thus, we verify that a GLOF in Degaco might only occur before 1966.

3.3.2.2. Chongbaxia Tsho. According to Komori et al. (2012), an anonymous lake was observed to experience an outburst flood from Landsat images acquired between 17 Nov. 2000 and 20 Nov. 2001 (Komori et al., 2012). Other studies (Yao et al., 2014; Liu et al., 2016) thought that this event occurred on 6 Aug. 2000. The source lake of this event was called as Longjiu Tsho in Yao et al. (2014) and Chongbaxia Tsho in Liu et al. (2016). Our analysis confirms that this event occurred in 2001 based on a range of Landsat observations, specifically between 5 Feb. and 4 Nov. 2001 (Fig. 7A). A GLOF event is usually named after its initial outburst lake. Therefore, we here name this event as Chongbaxia Tsho outburst flood (Fig. 7B).

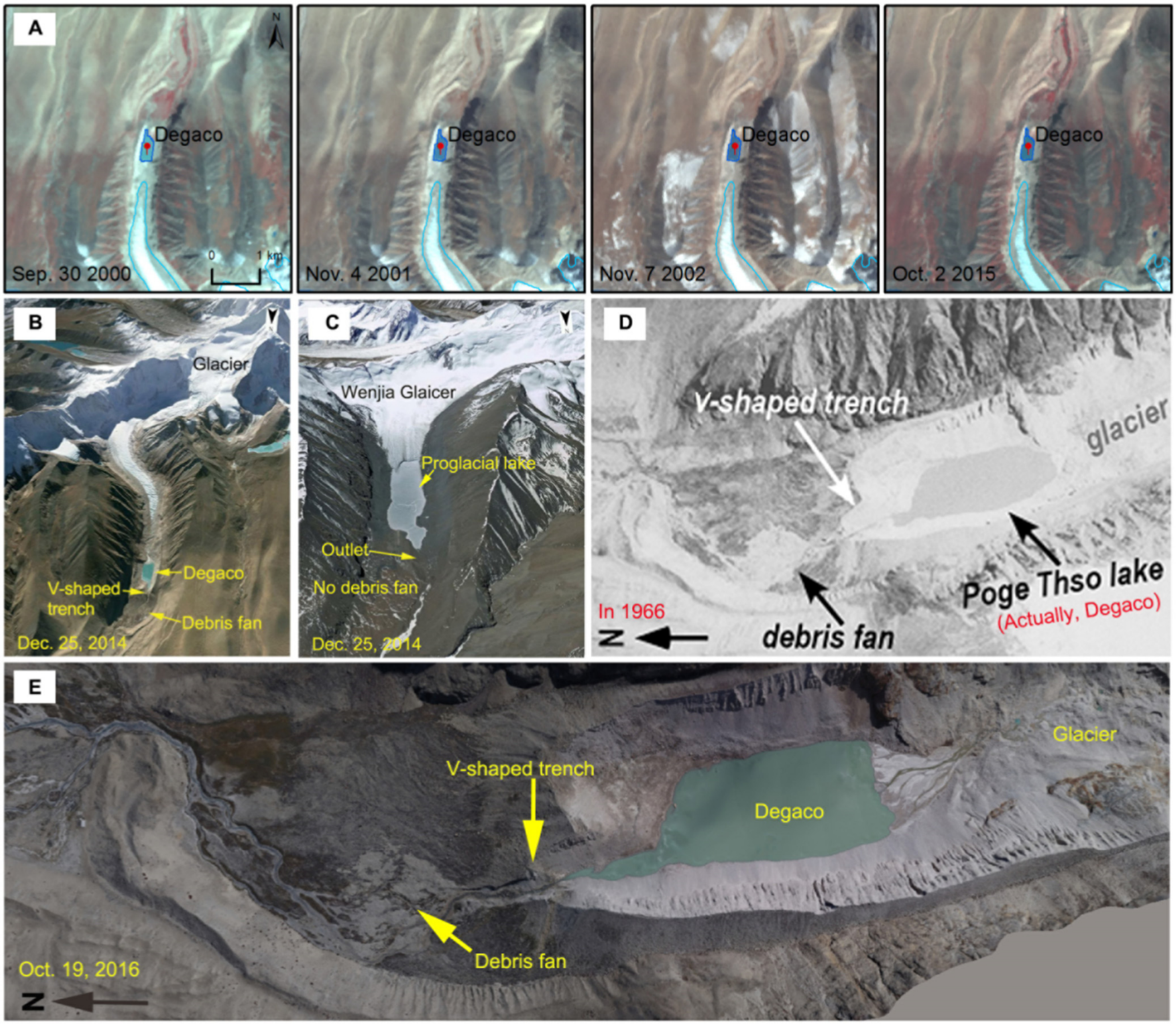

Fig. 6. Updating the characteristics of Degaco GLOF event using Landsat images (A), Google Earth (B, C), photos (D) modified from Komori et al. (2012) and our field photo (E).

3.3.2.3. Geiqu. The outburst from Lake Geiqu was first reported by Yao et al. (2014) based on their field surveys in 2009 and 2011. The lake area before outburst was estimated to be 0.05 km^2, and the outburst occurred between 24 June and 28 July 2010 using Huanjing (HJ) 1A/B imagery, which was possibly triggered by intensive precipitation or outflow from the upper lake (Yao et al., 2014). We here provide additional remote sensing evidence to support this event as a V-shaped breach, fresh debris deposit, and destroyed roads were clearly observable in Fig. 7C and D. The damage of this event was minor from its limited flooding volume. Two glacial lakes are observed in this basin. One lake has a cliffy edge (~70 m high) and was connected to a glacier upstream, while the other was moraine-dammed and disconnected from the glacier. Glaciers with a total area of 3.18 km^2 were distributed in the upriver basin. The horizontal distance between these two glacial lakes is 340 m. The downstream glacial lake was labeled as the initial outburst lake in Yao's et al. (2014) study.

3.3.2.4. Lemthang Tsho. A GLOF event on 28 June 2015 from the Lemthang Tsho (also known as Memari Tsho) was reported (Orlove, 2016; Shrestha et al., 2016). This flood washed away several bridges and caused some major landslides downstream but without any fatality because of a successful implementation of an early warning system (Gurung et al., 2017).

The location of this event was first identified by the Japan Aerospace Exploration Agency (JAXA) in a short time using Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR-2) data and Advanced Land Observing Satellite imagery (Nagai et al., 2016). JAXA shared their document and lake extent data on their website (http://www.eorc.jaxa.jp). Lamthang Tsho was believed to undergo a remarkable expansion from 8 Mar. to 23 Apr. 2015 and a remarkable shrinkage from 23 Apr. to 2 July 2015 (Nagai et al., 2016). However, long-term Landsat observations show that Lemthang Tsho shrank from 24 Dec. 1987 to 8 Mar. 2015, although the lake size remained relatively stable between 1989 and 2015 (Fig. 8) with an average area of 0.055 km^2. From another study (Gurung et al., 2017), a picture taken in May 2015 shows that Lemthang Tsho exhibited a normal extent compared with Landsat extracted water extent before the GLOF. Another picture demonstrates that Lemthang Tsho disappeared in late July 2015 (Gurung et al., 2017). Such evidence reveals that Lemthang Tsho's changes were very complex.

3.3.2.5. Outburst of a supraglacial lake on Tshojo Glacier. Komori et al. (2012) reported a supraglacial lake outburst case associated with the

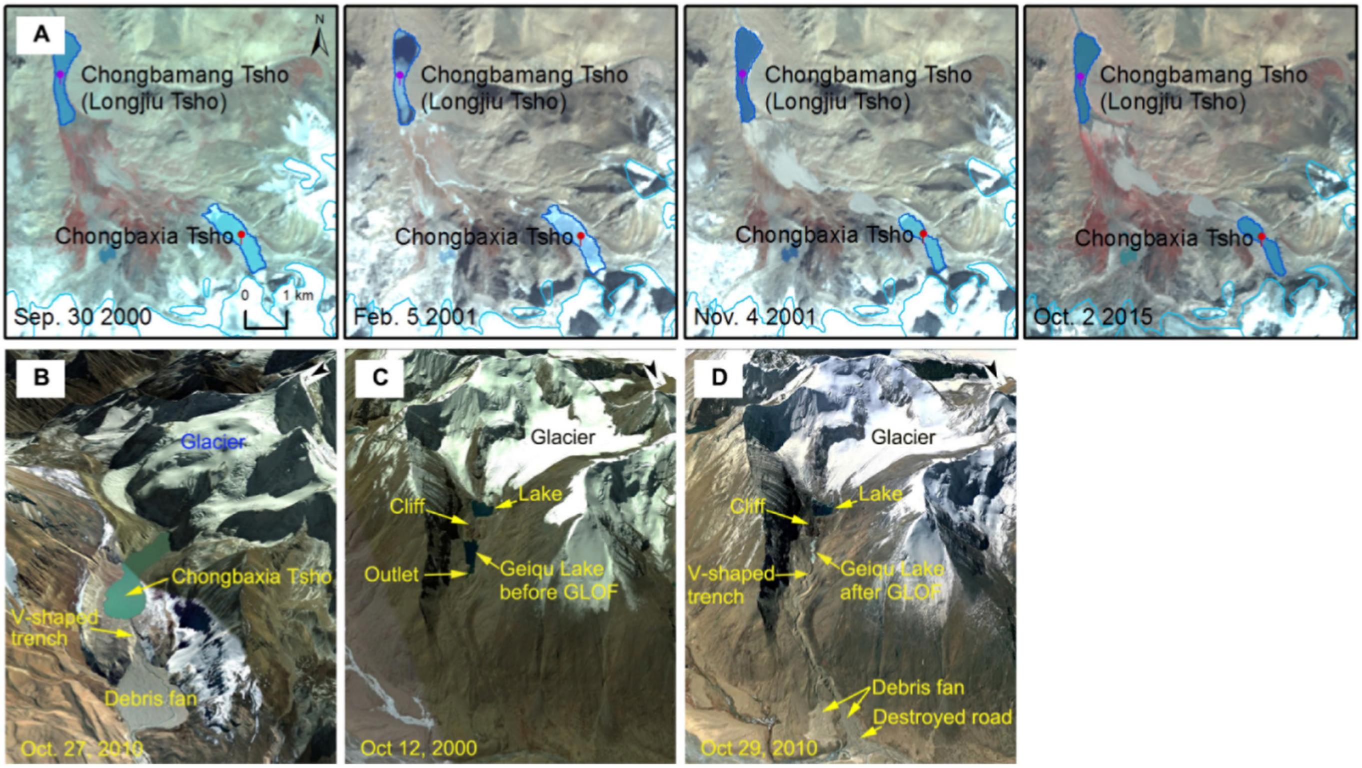

Fig. 7. Updating the Chongbaxia Tsho and Geiqu GLOF events using Landsat (A) and Google Earth imagery (B–D).

Tshiojo Glacier on 29 Apr. 2009. This event did not cause much damage because of its limited flood volume of 500 thousand m^3 recorded at a hydrological gauge in the Pho Chu River. Floodwater was supposed to be drained from a supraglacial lake on the lower part of the Tshojo Glacier, according to field survey and satellite images (Fig. 9A). The study of Komori et al. (2012) posed a hypothesis that leaking water of that supraglacial lake gushed out at the lower end of the Tshojo Glacier via englacial or subglacial channels and formed some sand and gravel mounds as well as a nontypical debris fan around the outlet (Komori et al., 2012).

Changes of supraglacial lakes from spillway or coalescence, including seasonal emergence, disappearance and expansion, can be highly dramatic in the Himalayas (Benn et al., 2001; Gardelle et al., 2011; Watson et al., 2016; Nie et al., 2017). The total area of supraglacial lakes in the red box of Fig. 9A, intersected with the water surface of the supraglacial lakes on 24 Apr. 2009, rapidly fluctuated from 1988 to 2015; and abrupt shrinkage of these supraglacial lakes was observed at least twice on the same part of the Tshojo Glacier (Fig. 9B). This fluctuation reveals the complexity of supraglacial lake evolution processes. GLOFs resulting from supraglacial lakes always have a close relationship with englacial or subglacial drainage systems for their limited water volume. This implies that the whole process of an outburst originated from a supraglacial lake via englacial and subglacial drainage systems is rather complex and still needs to be further explored.

3.3.3. Unpersuadable GLOF events

Four post-1990 flood events from Kabache Lake (Bajracharya et al., 2008; ICIMOD, 2011), Degaco (analyzed in Section 3.3.2.1) and

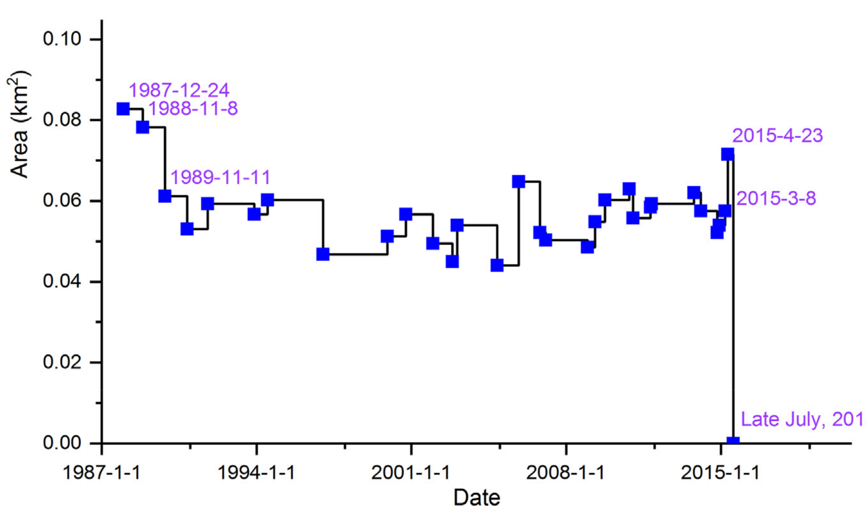

Fig. 8. Areal change of the Lemthang Tsho using Landsat images (between 24 Dec. 1987 and 8 Mar. 2015) and PALSAR-2 data (23 Apr. 2015).

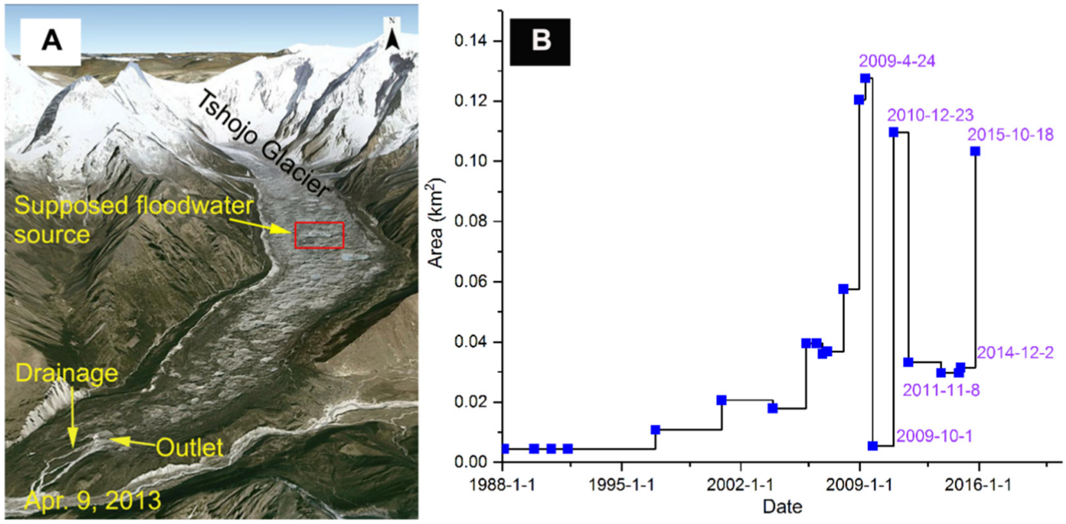

Fig. 9. Location observed from Google Earth (A) and areal change (B) of flooded supraglacial lakes on the Tshojo Glacier (red box).

Zhemaico (Liu et al., 2014; Yao et al., 2014) were verified to be unpersuadable GLOFs.

3.3.3.1. Kabache Lake. Two GLOF events from Kabache Lake were reported to occur on 15 Aug. 2003 and 8 Aug. 2004 respectively as a result of moraine collapse without any damage (ICIMOD, 2011). Although exact latitude and longitude coordinates were not provided in the report, Kabache Lake was successfully found from a map of GLOF events in Nepal (Fig. 10A). An evolution of Kabache Lake and the damage of the downstream valley were clearly recorded by a series of Landsat images from

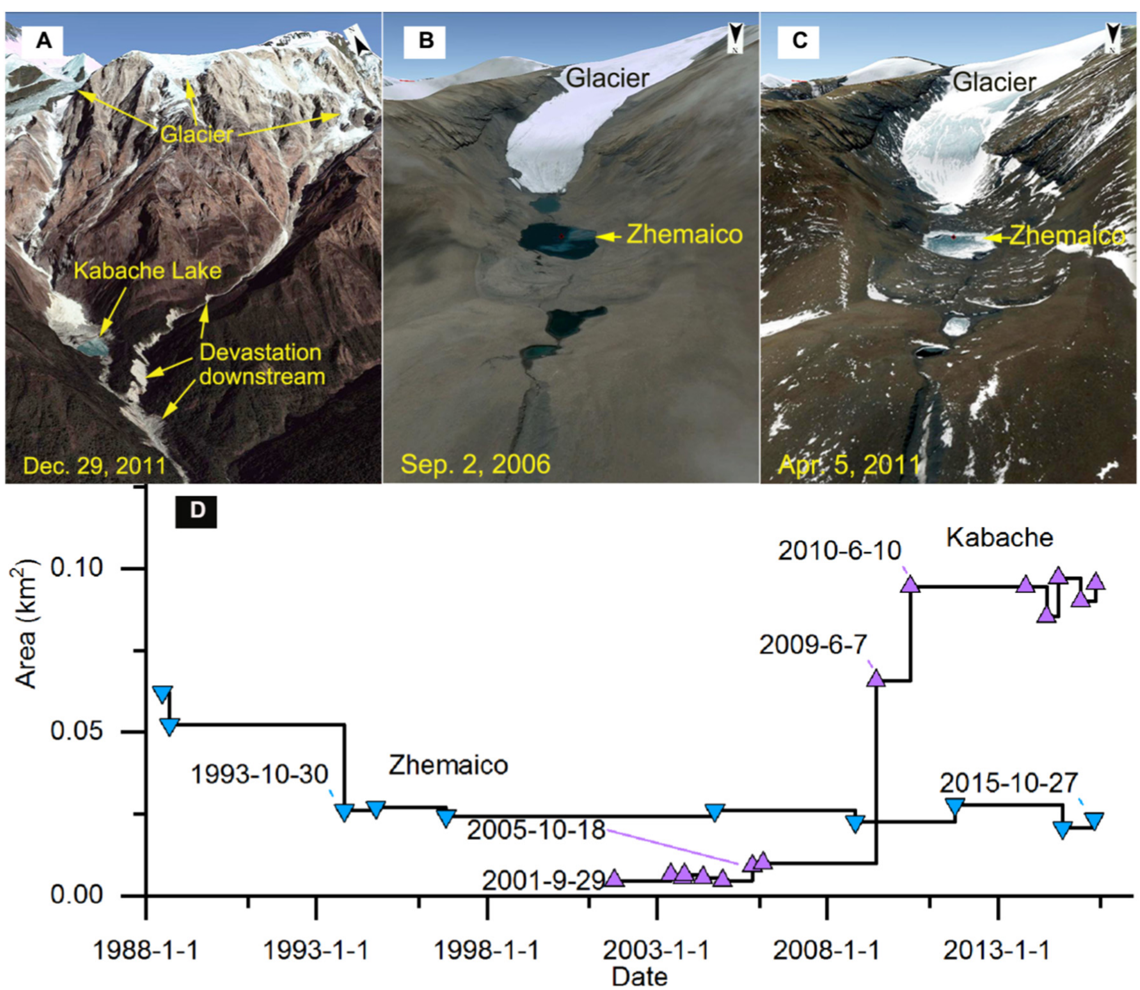

Fig. 10. Locations from Google Earth images (A–C) and Landsat-derived areal changes (D) for Kabache and Zhemaico.

1988 to 2015. A very small lake (~0.0045 km^2; initial Kabache Lake) first emerged in the Landsat image acquired on 29 Sep. 2001. The area of Kabache Lake was < 0.01 km^2 until the end of 2005, which could not cause a considerable flood from its limited water volume (Fig. 10D). A damage trajectory should be observed along the downstream valley if Kabache Lake indeed burst. However, no damage was seen in the nearest downstream valley of Kabache Lake. Instead, severe downstream damage was identified as a result of floods from another tributary (Fig. 10A). A devastated downstream valley confirmed the occurrence of two floods from satellite observations between 2003 and 2004. These floods, however, were not caused by the dam failure of a glacial lake because no lakes existed in the flooding source zone owing to the steep relief. We therefore confirm that these two events are typical mountain rainfall-induced flash floods rather than GLOF events.

3.3.3.2. Zhemaico. A flooding event from Zhemaico on 3 July 2009 was first reported by the Tibetan News Network, which destroyed downstream roads and bridges. Some studies introduced this event and provided its geographic coordinates (Liu et al., 2014; Yao et al., 2014). However, a V-shaped breach and corresponding debris fan were not observed in the remote sensing images (Fig. 10B and C). The altitudinal drop from Zhaimaico to the nearest small alluvial fan was just 2 m. Zhemaico remained stable between 1993 and 2015, with an area of 0.02 km^2 in 2015 (Fig. 10D). Additionally, the estimated volume of this lake was insufficient to result in the reported damage in the news. Previous studies located this lake based on the news description that did not give exact coordinates and assumed that this lake was the most possible one for the reported flooding event, in comparison with other lakes in the river basin (Liu et al., 2014; Yao et al., 2014). We believe that the labeled Zhemaico did not burst or cause a flood and that the source of floodwater was still unidentified if this flooding event were a GLOF. Thus, the reported event was likely only a flash flood.

4. Various statuses of glacial lakes after GLOFs

Three Himalayan glacial lakes, Cirenmaco, Ayaco and Jialongco, have repeatedly emerged and caused flooding hazards in the past decades. The Cirenmaco (also called Zhangzangbo, 86.065138°E, 28.067408°N) first burst in 1964. After water accumulation in 17 years, it burst again in 1981 and resulted in enormous loss downstream. Ayaco (86.493787°E, 28.348402°N) experienced consecutive outbursts in 1968, 1969, and 1970; and Jialongco (85.848126°E, 28.211274°N) burst twice on 23 May and 29 June 2002. These imply that multiple outbursts from the same glacial lake might occur with an interval from months to years. A repeated event, however, can only be suggested if rigorous evidence exists. Liu et al. (2014) indicated that Sangwangco burst twice in 1950 and 1954 without any reference, but we found no solid evidence for the 1950 event. The possibility of the outburst incident from Degaco in 2002, previously suggested by Yao et al. (2014) and Liu et al. (2014), also seems to be low, as demonstrated in our remote sensing analysis and field investigation (Section 3.3.2.1). These errors or controversies reflect our limited knowledge on the process and mechanism of repeated GLOF events because of lack of reliable data and the low accessibility to high mountain areas and call for continuous efforts in monitoring and inventorying Himalayan GLOFs (Dussaillant et al., 2010; Falátková, 2016).

Considering the possibility of repeated outbursts, the recent statuses of glacial lakes posterior to their outbursts need to be continuously monitored for downstream risk management. All 51 outburst lakes are categorized into three classes, namely disappeared lakes, stable lakes, and expanding lakes.

4.1. Disappeared glacial lakes after flooding

Several glacial lakes in the Himalayas perished after their GLOF events. Remote sensing observations provide strong evidence to confirm the disappearance of historical glacial lakes after outburst. A good case is Zanaco (Fig. S1a). Archival Landsat imagery revealed that this glacial lake burst on 7 June 1995 caused by ice avalanche. Its area rapidly reduced from 0.09 km^2 on 13 Oct. 1994 to 0.01 km^2 on 21 Dec. 1996. It eventually disappeared after 1996. The Machhapuchhre GLOF event, known as the earliest GLOF in the Himalayas, burst ~450 years ago based on geomorphological investigations (ICIMOD, 2011). Although details of the outburst process and damage are unavailable because of lack of reliable data such a long time ago, the outburst-induced outlet and lacustrine terrace are clearly preserved in recent high resolution images (e.g., acquired on 23 Dec. 2011 in Fig. S1b). Observed relics in the image also suggest two primary glacier retreats. We agree that this GLOF may have caused catastrophic damages according to the massive deposition of debris in the downstream valley. Choradari Lake (Fig. S1c) was a lateral moraine-dammed lake in the central Himalayas where water accumulated in summer (Das et al., 2015) but disappeared in winter during past the 25 years. The outburst event from this lake caused severe damage to a downstream village on 17 June 2013. This is the first reported GLOF event that originated from a lateral moraine-dammed lake and was induced by high rainfall intensity in the Himalayas. Choradari Lake completely perished after the outburst.

The other lakes in Fig. S1 were drained soon after their outbursts because of steep reliefs or broad outlets over the V-shaped breaches. They are Longda Tsho (Fig. S1d), Nare Lake (Fig. S1e), the pro-glacial lake on the Lunana Glacier (Fig. S1f), Chhubung (Fig. S1g), the lake on the Cuoalong Glacier (Fig. S1h), Lemthang Tsho (Fig. S1i), the supraglacial lake on the Lotse Glacier (Fig. S1j), and Gongbatongsha Tsho (Figs. S1k, S1l).

4.2. Stable glacial lakes after flooding

Most Himalayan glacial lakes remain relatively stable after the outbursts (Fig. S2). Fig. 11 shows the areal changes of 28 historically outburst glacial lakes in the Himalayas from ca. 1990 to 2015. Among them, 20 lakes burst before 1990 and then experienced little changes. Sangwang Tsho burst on 16 July 1954 and resulted in catastrophic downstream damages. Its area slightly expanded from 1991 to 2015. Sangwang Tsho is currently the largest post-outburst glacial lake in the Himalayas (with an area of 5.82 km^2 in 2015). Post-outburst lake dynamics in Fig. 11 was only inferred from the available monitoring period from ca. 1990 to 2015. For some of the lakes where outbursts occurred much earlier than 1990 (such as in the 1960s and 1950s), drastic area changes or fluctuations (expansions or shrinkage) might have occurred but are not observable from our acquired remote sensing images.

4.3. Rapidly expanding glacial lakes after flooding

As shown in their area dynamics during ~1990–2015 (Fig. 12), several glacial lakes were identified to have experienced evident expansion since the outburst, which raised concerns among the public and scientific communities given their potential secondary outbursts. Cirenmaco (Fig. 12A) expanded by 62.6% between 1988 and 2015, where risks were assessed by Nie et al. (2013) and Wang et al. (2015a). Jialongco flooded twice in 2002 and then rapidly expanded by 2015 (Fig. 12B). Another famous GLOF incident is a partial outburst from Luggye Tsho on 7 Oct. 1994 (Fig. 12C) that resulted in severe fatalities and damages. After the outburst, Luggye Tsho expended by 36.3% and reached 1.53 km^2 by18 Oct. 2015. The rapid expansion and increasing water storage in this lake has caught wide attention owing to its potentially extreme destruction once it outbursts again. Another three glacial lakes, Chubda Tsho (Fig. 12D), Gelhaipuco (Fig. 12E) and Lureco (Fig. 12F), where GLOFs all occurred before 1970, had significantly expanded (at least during ca. 1990 and 2015). A similarity of these six expanding glacial lakes is that they all started as proglacial lakes that contacted with mother glaciers. Terminal retreats of the mother glaciers created

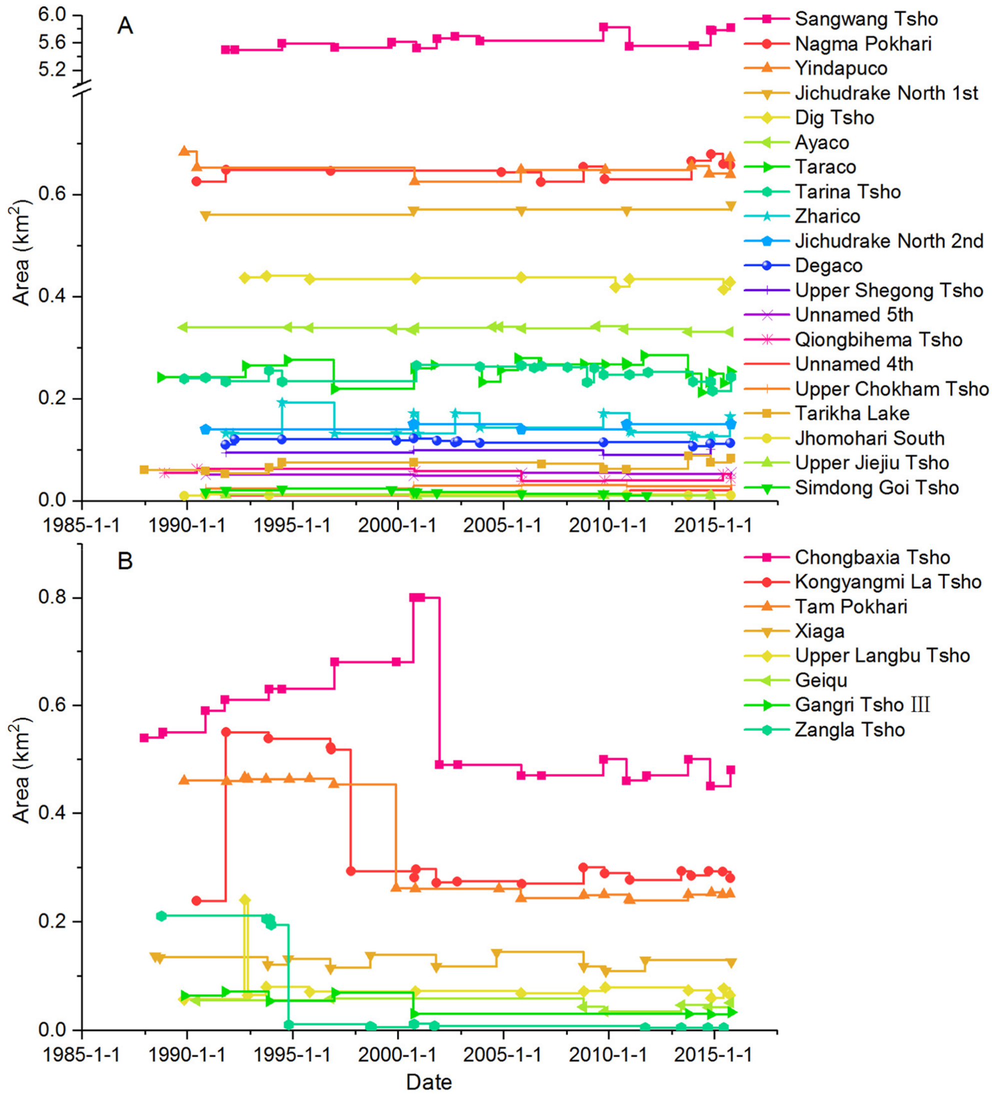

Fig. 11. Stable glacial lakes after outbursts: (A) flooded before 1990, (B) flooded after 1990.

additional space for upward lake expansion (Wang et al., 2015b; Song et al., 2016; Nie et al., 2017). In return, lake expansions further accelerated the glacier retreat as a result of thermal erosion (melting and calving) at the waterline (Sakai et al., 2009; Gardelle et al., 2011). This interaction between the lake and its mother glacier results in a continuous lake expansion and glacier mass loss until the glacier is detached from the lake or disappeared. For example, the terminal glaciers that feed Cirenmaco and Jialongco recently retreated behind the cliffy lake shelves (shown in Fig. 12A and B), which therefore obstructed further upward lake expansion.

5. Discussion

5.1. Chronological and seasonal frequencies of GLOF events

Out of the 51 persuadable Himalayan GLOF events, 35 are known with specific occurrence years, while the other 16 events are perceived to have occurred before 1975. Twenty-seven of the 35 events are known with specific outburst months. Chronologically (at 5-year intervals), most reported GLOFs are concentrated around the 1990s (Fig. 13A). A total of 17 glacial lakes experienced outburst incidents after 1990, and those lakes remained stable from the outburst dates to 2015, except Luggye Tsho and Jialongco. Fourteen out of 17 lakes can be well monitored and verified for GLOF by remote sensing images owing to an increasing capability of satellite observations (Table S1). GLOF events for Xiaga in 1995 and Geiqu in 2010 cannot be sufficiently confirmed by their areal changes from remote sensing images because of the topographic constraint by their cliffy edges. The 2002 Jialongco event was not effectively monitored because of substantial topographical shadow and high frequency of cloud contamination in the images.

Statistics based on the 27 well-recorded GLOF events show that all of them occurred between April and October (Fig. 13B) with the majority (18) occurring between June and August. Summarized in an annual cycle, the GLOF can start as early as early April, for example Dig Tsho event on 4 Apr. 1985, while the latest GLOF may happen in early October, such as Luggye Tsho event on 7 Oct. 1994. These statistics imply that GLOFs rarely occur during the frozen period from November to March. Rapid warming and precipitation during ablation season cause ice avalanches and generate massive glacier melt water (Chen et al., 2007; Liu et al., 2014), which are prone to trigger a GLOF as a result of dam failure.

5.2. Triggers of GLOF events

The most common cause of moraine-dammed failure in the Himalayas is mass movement (ice, snow, upper flood, precipitation, and/or rock) entering the lake (Fujita et al., 2008; Komori et al., 2012; Wang et al., 2012; Liu et al., 2014; Westoby et al., 2014a; Das et al.,

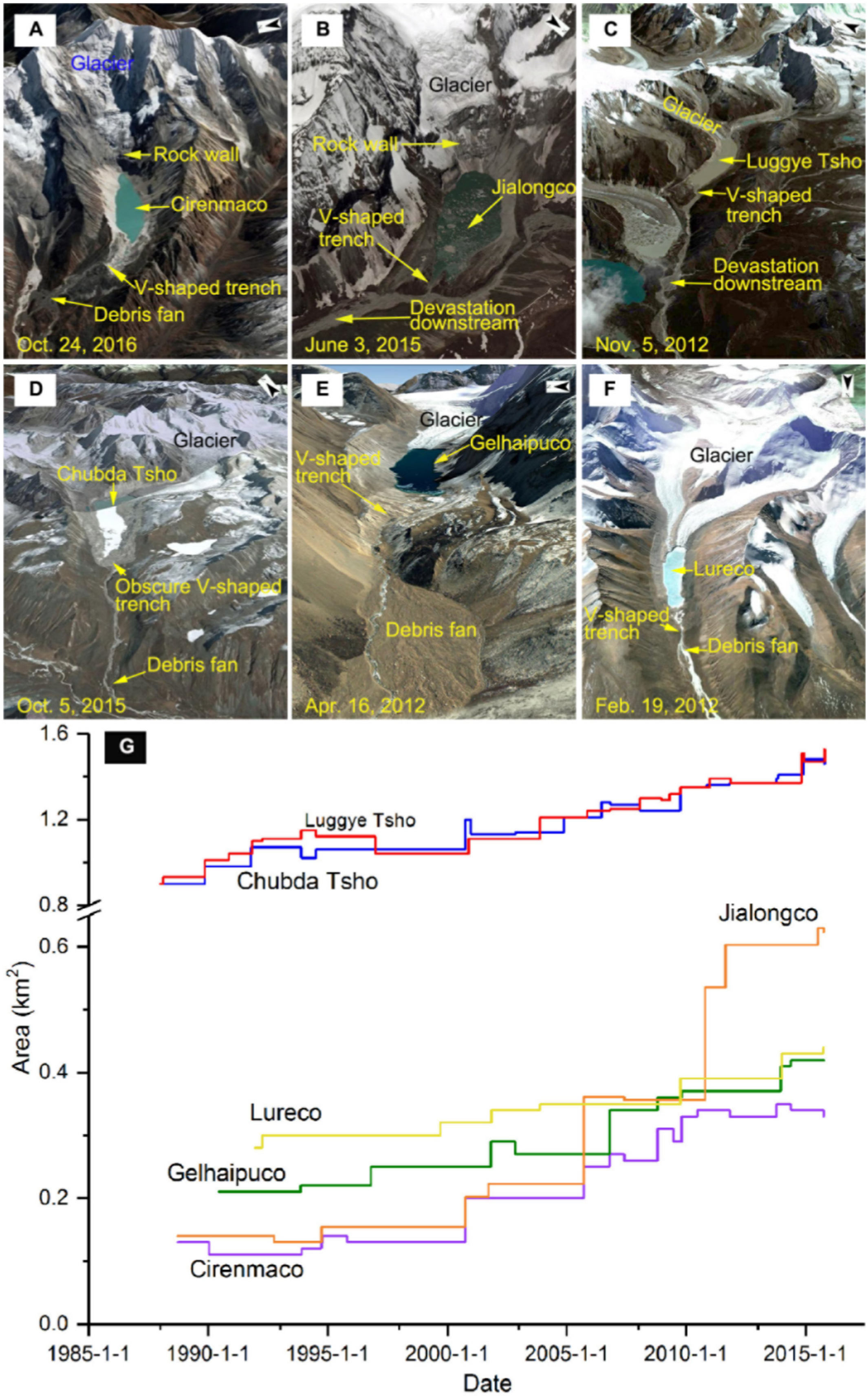

Fig. 12. Analyses from high-resolution Google Earth images (A–F) and Landsat-derived temporal area profiles (G) for six rapidly expanding glacial lakes after GLOF.

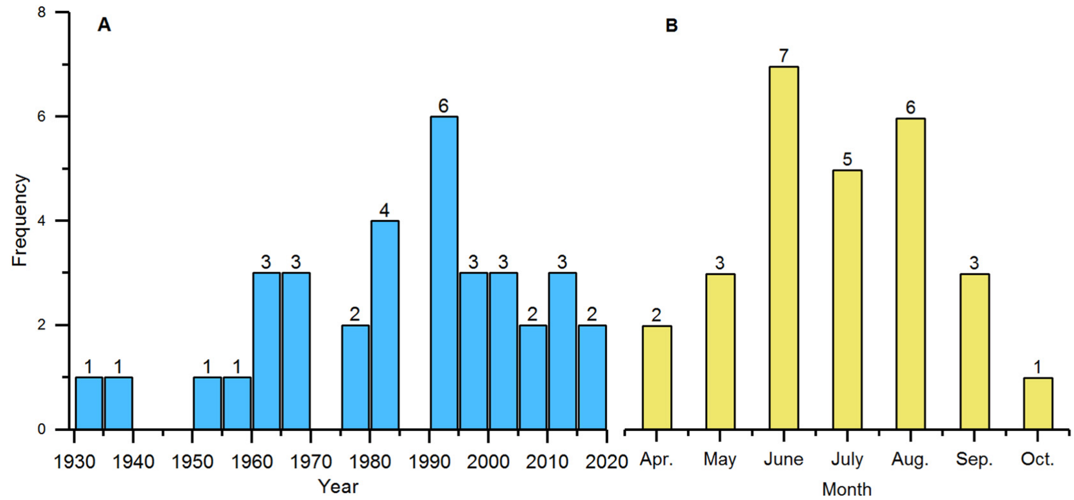

Fig. 13. Chronological (A) and seasonal (B) frequencies of historical GLOFs labeled with the number of outburst events.

2015; Rounce et al., 2016; Stoffel et al., 2016; Gurung et al., 2017) and subsequently overtopping and eroding the damming moraine (Rounce et al., 2016). Thirty-four of the 38 trigger-known events, such as Kongyangmi La Tsho event (Table S1), were caused by ice avalanche. Other triggers may include self-destruction induced by hydrostatic pressure, piping and/or degradation of an ice-cored moraine (Westoby et al., 2014a; Rounce et al., 2016), and seismic events (Westoby et al., 2014a; Gurung et al., 2017). Five GLOF events, such as outbursts from Yindapuco and Choridari lakes (Table S1), are known to be triggered by piping. The causes of some other outburst floods are still unknown because of lack of in situ observations. The integration of field investigation and remote sensing techniques will be increasingly important to unveil the triggers and processes of GLOF events.

Understanding GLOF characteristics and mechanisms helps us to predict and mitigate the outburst-induced disasters. A critical initial step is to distinguish GLOF events from flash floods induced by extreme precipitation, such as the incident from Kabache Lake (Bajracharya et al., 2008; ICIMOD, 2011), or debris flow without contributions of glacial retreating and melting, such as the incident from Langco (Mo et al., 2008). The most typical GLOFs in the Himalayas are the outbursts triggered by the failure of moraine-dams (Westoby et al., 2014a). Recent studies reported the sudden release of water from supraglacial pools (Komori et al., 2012; Kropáček et al., 2015; Rounce et al., 2017). Although these kinds of lakes did not result in considerable damages caused by their limited water volume, attention should also be paid to some newly formed large supraglacial lakes on debris-covered glaciers, such as supraglacial lakes on the Rongbu and Lalaga glaciers (Nie et al., 2017), which may lead to catastrophic disasters if they continue to expand in the future.

5.3. Implications and prospects

As in situ investigations of GLOFs are often prohibited by the remote and hostile alpine environments, remote sensing has been proven to be one of the most effective ways to identify GLOF events and monitor potentially dangerous glacial lakes. The contribution of remote sensing observations includes finding the source outburst lake by comparing lake areas before and after an outburst, interpreting geomorphological features at the outburst site, and analyzing the extent and intensity of outburst-induced loss and damages. Hydrological gauge observations, mass media reports, and socioeconomic loss summaries are also indispensable sources for cross-checking and further understanding GLOFs. The most severe GLOF events are those that result in fatalities and destructions of downstream infrastructures (Table S1). The impact of a GLOF is determined by outburst water volume, flood routing, and hazard-affected population. Because lake water volume is difficult to acquire, glacial lake area, which is directly observable from remote sensing images, has been used to infer lake water volume (Cook and Quincey, 2015). Some studies set a threshold of 0.1 km^2 to choose potentially dangerous lakes for hazard assessment (Wang et al., 2012, 2013). We here suggest a threshold of 0.05 km^2, given that considerable damages could also be caused by the outburst of smaller lakes, such as Choradari Lake and Zanaco (Table S1).

The growing capability of optical satellite sensors, such as onboard Landsat 8, Sentinel-2, and China's GaoFen, improves the ability of monitoring the evolutions of GLOFs and potentially dangerous lakes for improved early warning, emergency response, and disaster mitigation. The combination with synthetic aperture radar (such as PALSAR) further improves the monitoring capability under all-weather conditions in high mountain regions (e.g., Lemthang Tsho event in 2015 by Nagai et al., 2016, and Gurung et al., 2017). However, caution should be taken when identifying a GLOF event using remote sensing alone, particularly in case of lacking pre- and post-outburst observations. Many glacial lakes are with geomorphic characteristics (e.g., V-shaped trench and debris fan) similar to those of GLOF. The V-shaped trench and debris fan were widely distributed in alpine environment and could be also formed by weathering, erosion, and mass movements. In these cases, a more comprehensive method that integrates remote sensing observations, geomorphological interpretations, and socioeconomic statistics, as demonstrated in our study, will contribute to a more reliable inventory of GLOF events and thus disaster mitigation.

6. Summary and conclusions

This study provides a detailed inventory of Himalayan GLOF events using a comprehensive method with combination of satellite images, Google Earth high resolution imageries, geomorphic analysis, field investigations, and other relevant documents. The main conclusions include:

- A reliable database of GLOF events across the entire Himalayas was established through critical and comparative analyses, which advances our understanding of the spatiotemporal distribution of historical GLOFs. Eleven previously reported GLOFs from 10 lakes were identified to be unpersuadable. Quite a few erroneous or inaccurate GLOFs were corrected or updated. In addition, three new GLOF events were discovered, which occurred in 1992, 1994, and 1997, using archival Landsat images acquired before and after each outburst.

- Most glacial lakes (28 out of 46 lakes) remained stable after outburst, and seven lakes rapidly expanded inferred from our mappings using Landsat imagery acquired from ca. 1990 to ca. 2015 (Fig. 2). Eleven glacial lakes vanished after outburst. Historically repeated outburst events imply that more attention is needed for these rapidly expanded glacial lakes, such as Luggye Tsho and Jialongco.
- A total of 35 events with specific occurrence years reveal that GLOF hazards increased from 1975 to 1995 and slightly decreased from 1995 to 2015. The 27 events with detailed outburst dates show that historical GLOFs only occurred between April and October. The major trigger was ice avalanche.
- The increasing capacity of a remote sensing observation system will play a more crucial role in monitoring potentially dangerous glacial lakes and will provide early warning. The construction of monitoring and an early warning system is urgently needed for GLOF risk management in the Himalayas, including hydrological and meteorological observation networks in this critically vulnerable zone.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found in the online version, at https://doi.org/10.1016/j.geomorph.2018.02.002. These data include the Google map of the most important areas described in this article.

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